Ensemble Data Assimilation and Predictability of Tropical Cyclones

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LONG-TERM GOALS

The ultimate goal is to improve tropical cyclone track and intensity prediction through further development of ensemble-based data assimilation at the regional scale. More specifically, the objective is to make better use of in-situ and remotely-sensed observations in cloud-resolving models. In collaboration with scientists at the Naval Research Lab (NRL), we would like to develop an ensemble-based data assimilation system for the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) that is capable of assimilating remotely sensed data, as well as observations from convential meteorological networks, to improve tropical cyclone prediction. This work will build upon a protype COAMPS-based ensemble Kalman filter (COAMPS-EnKF) that has been recently developed at NRL following the success of the ensemble data assimlation system developed at the Pennsylvania State University (PSU) for the Weather Research and Forecasting (WRF) model.

OBJECTIVES

The primarily objectives of the proposed work are as follows: (1) Further develop the COAMPS-EnKF data assimilation system for tropical cyclone initialization capable of effectively assimilating airborne Doppler radar and satellite observations as well as data from conventional surface and sounding networks. (2) Implement a pseudo ensemble data assimilation system for COAMPS that is capable of ingesting flow-dependent background error covariance for tropical cyclone initialization without performing a computationally expensive online ensemble forecast. (3) Develop quality control and data thinning procedures for COAMPS-EnKF by implementing successful strategies from the pre-existing PSU WRF-based EnKF data assimilation system (WRF-EnKF). (4) Explore the practical use of different observing strategies in predicting tropical cyclones, including the assimilation of droposondes, radar, airborne and spaceborne observations using ensemble-based data assimilation systems.

APPROACH

Since the beginning of this project renewal on 1 February 2012, two doctoral students (Jonathan Poterjoy and Christopher Melhauser) have been dedicated to the project tasks at the Pennsylvania State University under the guidance of both PI's (Drs. Fuqing Zhang and Yonghui Weng) and NRL collaborators Dr. Allen Zhao and Jim Doyle. As a continuation of the previous ONR funding, Poterjoy

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focuses on the structure and sampling errors in tropical cyclone background error covariance, and its implications for ensemble data assimilation. His current work uses the WRF-EnKF framework, but the findings are transferable to the COAMPS-EnKF system that is being developed. He is also working on comparing and coupling the ensemble and variational data assimilation methods for tropical cyclone applications using past field campaign observations such as from multiagency experiments PREDICT and GRIP of 2010.

Melhauser, who started to work on the project since summer 2012, has successfully implemented COAMPS in the PSU computing environment. With some delays in the approval process, we have now successfully received the prototype COAMPS-EnKF code from NRL where it was originally developed. Our PSU team has been designing and implementing a fully functional hourly-cycling DA system using COAMPS-TC and the COAMPS-EnKF, incorporating the PSU P-3 airborne Doppler radar super observation operator.

We are also actively collaborating with Drs. Allen Zhang and Dr. Jim Doyle as well as other scientists at NRL to implement COAMPS and COAMPS-EnKF. Further development of the COMAPS-EnKF data assimilation is facilitated by transferring some existing capabilities from the WRF-EnKF system.

During the further development of the COAMPS-EnKF, and by comparing with our WRF-EnKF full-cycled and well-tested data assimilation system, we found some considerable challenges of using the COAMPS-EnKF at PSU, some of which are related to the PSU team's prohibited use/access to the NRL's variational data assimilation system (e.g., the initial and boundary perturbations for the COAMPS ensemble) while others related to the model numerics (e.g., the COAMPS model cannot easily recycle the model boundary layer properties such as TKE during each cycled run). We are working with our NRL collaborators to resolve these issues at the moment.

We have continued our real-time ensemble analysis and prediction of Atlantic tropical cyclones through 2013, assimilating airborne Doppler radar observations at a cloud-resolving model resolution. This work continues through collaboration with scientists who participate in the NASA Hurricane and Severe Storm Sentinel (HS3) field campaign using Global Hawk, and the NOAA Hurricane Forecast Improvement Project (HFIP). Through ensemble simulations and sensitivity experiments, we will continue to examine the flow- and regime- dependent predictability of tropical cyclones.

WORK COMPLETED

As a continuation and expansion of the PI's past ONR project that ended in 2011, we have made significant progress in improving our understanding of tropical cyclone predictability and further developed ensemble-based data assimilation methods for tropical cyclones. Now that we have successfully installed the prototype COAMPS-EnKF on the PSU computing cluster, we begin to add considerable capability to the COAMPS-EnKF by including the development of a new ensemble generation for boundary and initial conditions for the COAMPS model, the use of the P3 Doppler observations, and continuous cycling capability our ongoing focus will be on the development of the new data assimilation system. We also continue the use ensemble based data assimilation systems for studying the dynamics and predictability of tropical cyclones, along with determining affective observing strategies. The following tasks have been completed:

1) Successfully compile COAMPS v3.1.1 and v4.2.2 on the local PSU cluster
2) Successfully execute COAMPS v3.1.1 "bench" test and COAMPS v4.2.2 "newbench" test

3) Download NOGAPS and observation data from the GODAE server for Hurricane Karl (2010) and execute a full multi-domain analysis and model forecast

4) Successfully compile and execute COAMPS Utilities on the PSU cluster

5) Successfully compile and execute the NRL "getgfs" code to convert GFS 1^{o} and 0.5^{o} model output into NOGAPS data for COAMPS initial and boundary conditions

6) Successfully execute COAMPS v4.2.2 utilizing GFS initial and boundary conditions for Hurricane Karl (2010) utilizing observations and sea surface data (ghrsst) from GODAE

7) Successfully compile the COAMPS-EnKF system on the local PSU cluster

8) Designed a scalable method to construct an ensemble of forecasts from the GFS global model that can be ingested by the COAMPS-TC and COAMPS-EnKF system. An ensemble of forecasts is generated from a perturbation library valid over the season of interest. A modified version of the COAMPS *getgfs* program converts the perturbed ensemble members and deterministic forecast files to the NOGAPS-like files, compatible with COAMPS-TC.

9) Designed programs and driver scripts to center the ensemble in the COAMPS-TC framework, calculate the ensemble mean, and run COAMPS-TC/COAMPS-EnKF in a manner consistent with hourly cycling of the data assimilation system, in contrast to the current capability of 6-hour cycling.

10) Incorporated the PSU P-3 observation operator into the COAMPS-EnKF system. The airborne super observations can be ingested in tandem or separately from the current observations available from NAVDAS.

Currently, the PSU team is:

- Testing the cycling component of the PSU system. Issues performing a full model restart after the assimilation step have surfaced; some of the ingested model fields are being re-initialized. PSU is in contact with NRL to diagnose the source of the problem.
- Verifying the validity of the innovations generated using the PSU P-3 super observation operator in the COAMPS-EnKF. The magnitude and spread of innovations are reasonable, but a comprehensive verification cannot be performed until the cycling issue is resolved.

Over the next few months, the PSU team is:

- Planning to perform comparisons of the COAMPS-EnKF and PSU WRF-EnKF system, assimilating P-3 super observations. The GFS ensemble generation procedure has been designed to provide similar initial and boundary conditions to COAMPS and WRF, before interpolation to the each models respective grid.

The PSU team has made slow and steady progress, but lack of documentation, impeded access to the NAVDAS system, and lack of system specific observations have significantly impacted the speed and efficiency of the project. The lack of documentation has led to trial and error procedures to determine functionality and model operation procedures; a slow and incomplete approach.

RESULTS

Highlights of the work completed over the past year since the start of the renewal project are listed below.

(1) *Mesoscale dynamics and predictability of tropical cyclones and hurricanes (Stern and Zhang 2013a,b; Xie and Zhang 2012; Xie et al. 2013; Zhang and Tao 2013; Munsell et al. 2013; Fang and Zhang 2012; Melhauser and Zhang 2012)*: The use of probabilistic methods and ensemble analysis to investigate the genesis dynamics and predictability of Tropical Storm Erika (2009), Hurricane Karl (2010), Typhoon Morakot (2009), Super Typhoon Megi (2010) during ITOP, as well as through ensemble simulations of idealized tropical cyclones with and without wind shear. It is found that at least for some cases, the predictability of tropical cyclones may be limited by the randomness of moist convection and the uncertainties in representing features of the larger-scale environment, including the environmental wind shear and moisture distribution.

(2) *Improve tropical cyclone track and intensity prediction through further development of the regional-scale, cloud-resolving ensemble-based data assimilation and prediction system capable of efficiently assimilating ground-based and airborne Doppler and to examine the efficiency of observation targeting (Poterjoy et al. 2013; Weng and Zhang 2012; Green and Zhang 2013a,b; Sippel et al. 2013; Aksoy et al. 2012; Jung et al. 2012; Zhang and Weng 2013).* We examined the performance of the ensemble-based data assimilation and prediction system with Doppler radar observations systematically for all the 2008-2012 storms that had airborne Doppler missions. We also began including the HIWRAP airborne Doppler observations from Global Hawk into the set of observations to be assimilated. Our findings show that ensemble analyses and forecasts that include Doppler wind observations can notably improve the track and intensity prediction while revealing significant uncertainty in the forecast.

(3) *Intercomparison and hybrid of ensemble with variation method (Zhang and Zhang 2012; Zhang et al. 2013a,b; Poterjoy and Zhang 2013a,b).* We have performed by far the most extensive comparison of 3DVar, 4DVar, EnKF, and EnKF-3DVAR and EnKF-4DVAR hybrids at the regional scale, demonstrating clear benefits of the hybrid approaches. The pseudo-hybrid ensemble data assimilation (PEDA) system we developed is capable of assimilating inner-core observations with vortex-dependent error covariance without an online cloud-resolving ensemble. We also further performed coupling and inter-comparison of EnKF and 4DVAR for tropical cyclones. It is further demonstrated that the clear advantage of using ensemble based background error covariance in a 4DVAR system. In the case study of the genesis of Hurricane Karl (2010), it is found the EnKF-4DVAR system can improve the practical predictability of the genesis by as much as 1-2 days with similar computational costs.

(4) *Further development of the COAMPS-EnKF software and its implementation in the PSU computing environment:* The prototype COAMPS-EnKF code developed by Dr. Allen Zhao at NRL was based on the WRF-EnKF, a system developed by the PI that is capable of assimilating in-situ and remotely-sensed observations including radar data. Our PSU team has been designing and implementing a fully functional hourly-cycling DA system using COAMPS-TC and the COAMPS-EnKF, incorporating the PSU P-3 airborne Doppler radar super observation operator. We also developed a new ensemble generation method that can be used to generate initial and boundary conditions for the COAMPS-EnKF.

IMPACT/APPLICATIONS

Understanding the limit of tropical cyclone predictability and the associated error growth dynamics is essential for setting up expectations and priorities for advancing deterministic forecasting and for providing guidance on the design, implementation and application of short-range ensemble prediction

systems. Understanding the nature of tropical cyclone predictability is also crucial to the design of efficient data assimilation systems for tropical cyclones. Advanced ensemble-based data assimilation systems that are capable of assimilating both Doppler radar and satellite observations are very promising for the future cloud-resolving ensemble prediction of tropical cyclones.

TRANSITIONS

In collaborations with scientists at NRL in Monterey, the WRF-based ensemble data assimilation system that is partially sponsored by this project is currently being transferred to the Navy mesoscale prediction model, COAMPS, with the potential to be used in future operational forecasts.

The ensemble-based data assimilation system is also currently being used for quasi-operational hurricane prediction system as part of the NOAA's stream-1.5 runs of the Hurricane Forecast Improvement Project.

The ensemble-based data assimilation system is also being used by NASA scientists for assimilating HIWRAP airborne Doppler radar observations from Global Hawk for the GRIB/HS3 program.

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HONORS/AWARDS/PRIZES

2012 PI **Zhang** won the inaugural ***Paul F. Robertson Award for the EMS Breakthrough of the Year***, Penn State University

2013 Graduate Student **Jonathan Poterjoy** funded by this grant won the ***best student oral presentation award*** at the American Meteorological Society's Conference on Mesoscale Processes